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Impact Of Open-pit Mining Expansion on Slope Stability at Pt. Hikari Jeindo, Langgikima, North Konawe, Indonesia

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Abstract

Expansion of mining pit is associated with an increased risk of slope instability and high costs. This is because changes in geometry of the mine slope significantly affect slope stability, alter the stripping ratio, and potentially threaten the continuity of mining operations. Therefore, this research work aimed to investigate the impact of changes in geometry of mining pit on slope stability to provide insight into safety, economic assurances, and ensure the sustainability of mining operations. This research work was applied by the 2D numerical modeling method using the Slide Software V. 6.0 Rocscience to analyze geometry of mining pit and impact on slope safety factors. The investigation was conducted at Pit Block A of Pt. Hikari Jeindo, managing nickel mining activities in the Langgikima District, North Konawe, Regency, Southeast Sulawesi Province, Indonesia. The results showed that the modeling method successfully showed changes in slope geometry, ensuring safe and economically viable slope safety factors. However, to obtain a more comprehensive understanding of slope stability conditions, a 3D numerical modeling method is required to capture the area affected by expansion of mining pit.

1. Introduction

The high demand for nickel ore is significantly increasing mining production targets [1, 2, 4, 5], leading to expansion of open-pit mining pit. This expansion can cause an elevated risk of slope instability and mining costs, as changes in geometry of the mine slope impact slope stability values and stripping ratio, threatening the continuity of mining operations. Consequently, precise analysis is required to investigate the impact of changes in open-pit mining on slope stability to ensure safety, sustainable operations, and economic viability [4, 16, 18].

In open-pit mining, stabilization is required to prevent slope failure, specifically during mining operations [12]. Slope stability analysis is one of the most essential issues in mining and geo-technical engineering [19, 23]. This is because neglecting the parameters in geotechnical can lead to significant losses in worker and equipment safety, time, production, including capital. A previous research work has shown that slope instability can result in the failure and collapse of engineering structures [25]. Therefore, slope stability must be analyzed, considering various aspects with adequate precision, using appropriate methods. Expansion of open-pit mining can increase the production of excavated materials, impacting the height of pit walls, material stockpiles, and heap leaching. Specifically, deeper, and steeper changes in open-pit mining can enhance the sensitivity of slope stability analysis, which requires more advanced analysis and design methods [14].

The design of geometry and implementation must be carried out in various stages to ensure structural safety and minimize the volume of material excavated, thereby reducing the overall project costs [8]. Determination of the optimal slope is also crucial, as achieving optimal slope angles has high economic value, ensuring the safety of workers and equipment in open-pit mining. To create an optimal slope design,

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Corresponding author: 17sahrulpoalahi@gmail.com (S. Poalahi Salu) geotechnical work includes altering slope geometry, which changes volume and affects the stripping ratio value, also known as mining recovery value. [4, 18].

Generally, one of the most critical purposes of open-pit mine planners is to maximize the net present value [12]. Therefore, in the first step, the practical factors of break-even stripping ratio, cutoff grade, block economic value, and open-pit slope are considered the essential parameters in the design and production planning steps (Hustrulid, W.A. 1995; Rendu, J.M. 2014) [3].

Several research have addressed the impact of changes in geometry of open-pit mining on slope stability values and the economic aspects (Sjöberg, J., 1996). These include a review of large-scale slope stability in open-pit mining by Stacey, TR., *et. al.* (2003), new slope stability considerations for deep open-pit mines (Zhang, F., *et. al.*, 2021), and assessment of the rock slope stability of Fushun West Open-pit Mine (Zebarjadi Dana, H., *et. al.*, 2018). The effects of geometrical and geomechanical properties on slope stability of open-pit mines have also been investigated using 2D and 3D finite difference methods (Zhou, Y., *et. al.*, 2020). Furthermore, a research work on high and steep slope stability and slope angle optimization in open-pit mining has been conducted based on limit equilibrium and numerical simulation.

2. Literature Review

2.1. Slope

Slope is a surface of the earth that forms a certain angle with the horizontal plane due to changes in various locations caused by exogenous and endogenous forces [12]. Whether natural or artificial; the shape of slope depends on erosion, soil movement, and weathering. Specifically, slope is a significant consideration for civil, mining, and rock engineering professionals during project design [7, 25].

Mining slope is intentionally formed with specific angles based on stability factors, stripping ratios, and recovery values. Moreover, slope with geomaterial, soil, and rock material has different characteristics that must be thoroughly understood [8, 12, 19]. In excavating soil or rock masses that are highly fractured and eroded, the most unstable failure surface often takes on a circular arc, particularly in the absence of geological structure controlling the failure [9]. Since soil behavior influences slope stability analysis, soil properties become significant inputs for accurate precision in numerical models through several direct field investigations [7, 17, 14, 19].

2.2. Analysis of slope stability

The safety factor is calculated based on the limit equilibrium theory. Generally, slope stability is defined using the concept of the safety factor (FoS), determined by the ratio between the maximum resisting force and the driving force acting along the failure surface. Theoretically, slope is considered stable when the FoS is more significant than one. In practice, the theoretical safety level must be adjusted for the accuracy of input data. For short-term stability analysis, safety factor from 1.2 to 1.3 are acceptable, while values between 1.4 and 1.5 are considered suitable for long-term analysis. During this analysis, prudence is required, considering both average and realistically lower values of mechanical parameters as the basis of the design process [14].

Stability of slope depends on the magnitude of resisting and driving forces on the potential failure surface. Resisting forces are responsible for counteracting the occurrence of failure while driving forces trigger failure. Factors influencing slope stability include geometry, geological structure, physical and mechanical properties of the soil, including, groundwater conditions, and external forces [12]. In the limit equilibrium method, the shear strength of the slide surface and the force required to maintain the balance are evaluated and compared to calculate the safety factor [3]. In the analysis of circular failure, the sliding mass is divided into vertical slices, which are used for stability analysis. When equilibrium conditions exist for each component, the values obtained are established for the sliding mass. Therefore, the number of equations required for the analysis depends on the two factors of equilibrium conditions and slices. Specifically, two important limit equilibrium methods required are the modified Bishop and Janbu methods (Wyllie, D. and Mah, C. 2004) [3].

In this research work, the simplified version of Bishop limit equilibrium method was used due to simplicity, quickness, and provision of safety factor calculations that are reasonably accurate. In the modified Bishop method, it is assumed that the slip surface is entirely circular, with a horizontal force in the interface of slices intended for analysis. Considering the Mohr-Coulomb failure criterion, safety factor is calculated as follows (Wyllie, D. and Mah, C. 2004) [3]:

$$FoS = \frac{\Sigma \dfrac{[c + (\gamma_r h - \gamma_w h_w) tan\varphi](\frac{\Delta x}{cos\psi_b})}{1 + \frac{tan\psi_b \, tan\varphi}{FS}}}{\Sigma \left[\gamma_r h \Delta x sin\psi_b + \frac{1}{2}\gamma_w Z^2 \frac{\alpha}{R}\right]} \quad (1)$$

Where FoS is the safety factor, and γr is the unit weight of soil or rock, γw is the water unit weight, h is the slice height, Hw is the water height within the slice, ψb is the base angle of the slice, c is the cohesion of the slip surface, φ is the friction angle of the slip surface, Δx is the slice width, Z is the water depth within the tension crack, R is the slip radius, and α is the distance between the failure arch centre and two-thirds of the depth of the tension crack.

The critical failure circle location from Bishop method usually closely approximates field observations. Therefore, Bishop method is mostly preferred to provide more accurate adjustments, which require experimentally determination of the sliding surface with the most minor safety factor. When the sliding surface is considered circular, grids must be created where each intersection point of its lines represents the center of the circular failure circle.

2.3. Processing and modeling software slide V. 6.0

Numerical method is essential for engineering design projects and stability control [24]. This is due to the numerous advantages of applying numerical simulation modeling and limit equilibrium method in predicting slope stability. The method considers stresses on slope body and analyzes deformations and stability, showing the mechanisms of deformation and slope failure [22].

Several research have used numerical modeling to analyze slope stability in 2D and 3D, such as Chand, K. and Koner, R. (2023). These include internal mine dump slope stability and failure zone identification using 3D modeling (Walia, A. and Roy, A. K., 2022), Assessment of slope stability and its remedies in Palampur, Himachal Pradesh (Sarfaraz, H. et al., 2022), numerical modeling of slide-head-toppling failure using FEM and DEM methods (Hussain, S. et al., 2021), proposing a viable stabilization method for slope in a weak rock mass environment using numerical modelling: a case study from cut slope (Sarfaraz, H. et al., 2021). Other investigations include numerical stability analysis of undercut slope evaluated by response surface methodology (Goshtasbi, K. et al., 2008), Slope modification of open pit wall using a genetic algorithm-case research southern wall of the 6th Golbini jajarm bauxite mine (Ataei, M. and Bodaghabadi, S., 2008), comprehensive analysis of slope stability and determination of stable slope in the Chador-Malu iron ore mine using numerical and limit equilibrium methods (Alikhani, A. et al., 2020), and investigation of Bishop and Janbu models capabilities on slope stability problems with special consideration to open-pit mining operations [20].

Among several methods that have been investigated, 2D slope stability analysis is mostly used to evaluate slope stability. This method depends on a simple generalization and expanded history, forming the basis for slope stability analysis (M. D. Fredlund, D. G. Fredlund, and L. Zhang) [20]. In most cases, 2D slope stability analysis provides a more conservative estimate (smaller FOS) than 3D analysis [12,15,18,21,22]. Compared to 3D, the use of 2D offers various advantages such as ease of execution, requires lower precision and converges to a specific FoS [24]. Similarly, data input and output interpretation in 3D slope stability analysis are more challenging and complex [18].

The limit equilibrium analysis Slide 2 with the method of shear strength reduction is one of the popular methods for slope stability analysis [12]. Rocscience Slide 2D is a specialized geotechnical software for slope stability calculations, as one of the programs in Rocscience geotechnical calculation package, which includes Swedge, Roclab, Phase2, Rocplane, Unwedge, and Rocdata. Generally, the steps for slope stability analysis with Rocscience Slide consist of modeling, identification of calculation methods and parameters, material, determination of the sliding surface, execution/calculation, and interpretation of FoS values using a software called Slide-Interpret [10, 11, 13].

3. Material and Methodology

This research work began with direct observations at the field research location. The types of data obtained were classified into two categories, namely primary and secondary. Specifically, primary data was collected directly in the field, which included boreholes such as throat, geological, and survey data. Secondary data was obtained and processed by the company, including analysis, IUP (mining permit), topography, cutoff grade (COG), and geotechnical data (physical and mechanical properties of the soil).

The next stage included data processing, where resource and reserve estimation and numerical modeling simulations for various slope geometry based on the final mining limits were conducted. Surpac 6.5 was used to estimate resources and reserves, developing the final mining plan (pit limit) using the Lerchs-Grossman algorithm. This Surpac 6.5 is a software released by Gemcom. Inc., which is used for mine management in both open-pit and underground mining. Gemcom Surpac 6.5 offers functions for drawing horizontal and vertical curves, hole planning, volume calculations, and plot design.

Slide 2D is used to create various mine slope geometry such as height, width, including angle, and analyze safety factor (FoS) for each slope geometry. This is followed by the selection of geometry that meets slope safety standards, specifically FoS > 1.5, by the regulations of the Ministry of Energy and Coal, Mineral Resources, Republic of Indonesia [9].

3.1. Research location

The research area, located in Block A of Pt. Hikari Jeindo, is characterized by an IUP area of approximately 177 hectares and a Block A of 48 hectares. The exploration activities include drilling to obtain material samples. Subsequently, the drill samples are tested in the laboratory to determine the Ni content. A total of 18 drilling points are obtained in Block A, with an average drilling depth of approximately 17 meters.

The research location is approximately 167 meters above the sea level, obtained from survey results or direct field measurements. These topographic data is used as the initial mining elevation and a reference boundary when modeling or planning mining levels. The topographic map of the research area is shown in Figure 2.

3.2. Block modeling and resource estimation

The modeling of lateritic nickel ore resources was conducted using the Surpac software version 6.5, with block dimensions of 25 m in length, 25 m in width, and 1 m in thickness. For sub-blocks, the dimensions include 12 m in length, 12 m in width, and 1 m in height. Subsequently, the inverse distance weighting method was applied to estimate the lateritic nickel resources, determining grades for each block, which were distinguished based on the color of each block. The distribution model of nickel resources in the research area is shown in Figure 3.

Based on the color of each block, classification was grouped into several classes, including a waste, low-grade, medium-grade, and high-quality saprolite class with grades <1.49, 1.5-1.69, 1.7-1.89, and >1.9. The distribution model and estimation of nickel resources in Figure 3. The results of the economic nickel-laterite resource estimation, categorized by Ni grades are presented in Table 1**.**

3.3. Ultimate pit limit design

After estimating lateritic nickel resources in the research area, the ultimate pit limit of mining is designed to determine mining boundaries and the materials extracted. The ultimate pit limit of mining design is divided into three designs, each with a different slope geometry or angles. The first, second, and last, pit model has geometry with slope angle of 55°, 60°, and 65°, respectively. The resource and reserve estimates for each ultimate pit limit design are shown in Tables 2, 3, and 4.

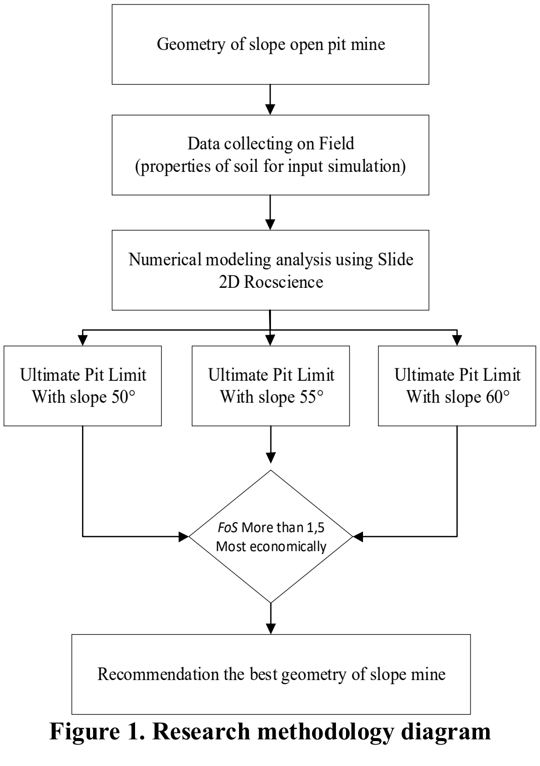


Figure 1. Research methodology diagram

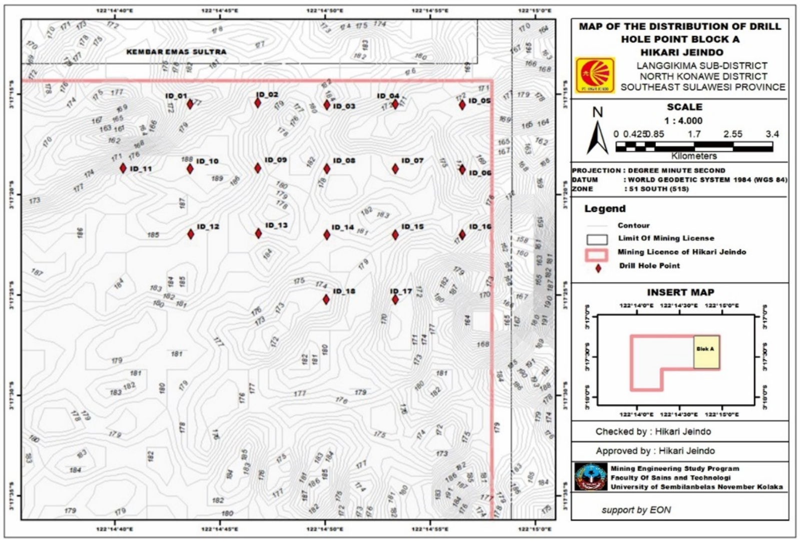


Figure 2. Topographic map and borehole distribution.

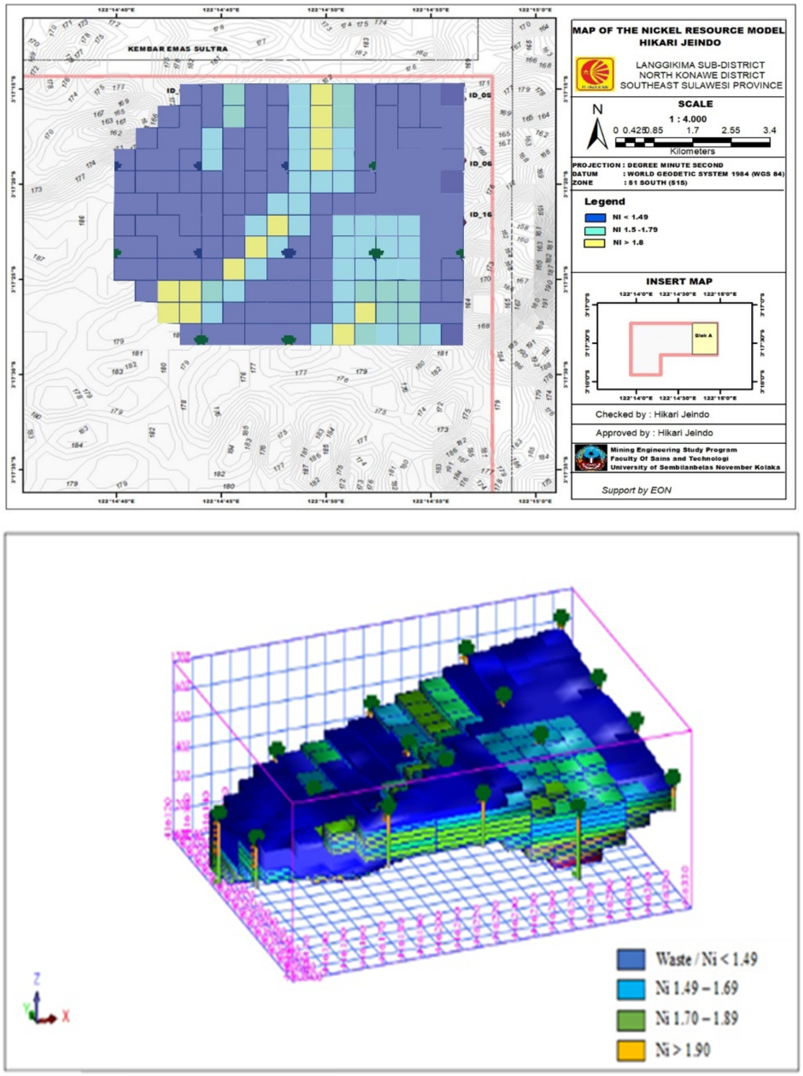


Figure 3. Ni resource model map on block A in 2D and 3D.

Table 1. Estimation of nickel-laterite resource.

Ore class	Volume (m^3)	Tonnage (mT)	Ni average (%)	Fe average (%)
Low-grade saprolite	40.450	60.675	1.6	9.3
Medium-grade saprolite	37.425	56.137,5	1.8	10.25
High-grade saprolite	27.350	41.025	2.15	10.85
Total	105.225	157.837,5	1.85	10.13

Table 2. Estimation of mined material for an angle of slope bench 55^0

Ore class	Volume (m^3)	Tonnage (mT)	Ni average (%)	Fe average (%)
Low-grade saprolite	40.450	60.675	1,6	9,3
Medium-grade saprolite	37.425	56.137,5	1,8	10,25
High-grade saprolite	27.350	41.025	2,15	10,85
Total ore	105.225	157.837,5	1,85	10,13
Waste	253.275	379.912,5	0,75	6,25
Total	358.500	537.750	1,3	8,19

Table 3. Estimation of mined material for an angle of slope bench 60^0

Ore class	Volume (m^3)	Tonnage (mT)	Ni Average (%)	Fe Average (%)
Low Grade Saprolite	40.450	60.675	1,61	9,27
Medium Grade Saprolite	37.425	561.37.5	1,81	10,29
High Grade Saprolite	27.350	41.025	2,15	10,95
Total ore	105.225	157.837,5	1,852	10,17
Waste	240.025	360.037,5	0,79	6,43
Total	345.250	517.875	1,32	8,3

Table 4. Estimation of mined material for an angle of slope bench 65^0

Ore class	Volume (m^3)	Tonnage (mT)	Ni average (%)	Fe average (%)
Low-grade saprolite	40.450	60.675	1,6	9,29
Medium-grade saprolite	37.425	561.37.5	1,8	10,23
High-grade saprolite	27.350	41.025	2,14	10,84
Total ore	105.225	157.837,5	1,85	10,12
Waste	231.150	346.725	0,79	6,44
Total	336.375	504.562,5	1,32	8,28

3.4. Value of overburden ratio in mine planning

After estimating the volume of extracted ore material, the stripping ratio is calculated for the ultimate pit limit design. The ore and waste material volumes are obtained through the result calculations from surface modeling for each ultimate pit limit design created. The stripping ratio value is obtained by comparing the total volume of overburden material to be stripped with the total volume of recoverable ore. Moreover, the calculation results are presented in Table 5.

3.5. Analysis of slope in pit block A

Stability of an overburden material in open pit is required to meet the minimum stability criteria according to Bowles (1989) for both individual and overall overburden. Bowles stated that a heap with a safety factor (FoS) value > 1.25 is considered safe. [6]. Therefore, the design of safe and stable slope is essential as the success of mining process is determined by the presence of safe slope conditions.

This research work was conducted on the actual slope. Based on mining design model using data such as material properties and slope geometry, slope stability analysis of pit Block A can be performed.

Table 5. Stripping ratio of pit design.

Pit design	Stripping ratio
Pit 1 design (55° slope of bench)	2.40
Pit 2 design (60° slope of bench)	2.28
Pit 3 design (65° slope of bench)	2.19

3.6. Material properties data

Material properties data, including soil type, layer thickness, unit weight, cohesion, and internal friction angle, are secondary data obtained from laboratory tests conducted by Pt. Hikari Jeindo. These tests cover the physical and mechanical properties of the soil and the results are shown in Table 6.

3.7. Geometry of slope

A single and slope designs for open-pit mining were obtained using Surpac modeling based on slope geometry data obtained directly in the field. For slope geometry of pit in Block A, the cross-section method was determined along the profile path to represent the entire slope geometry shape in Block A. Section A was created from west to east for angles of slope 55°, 60°, 65°, as presented in Figure 4, 5, and 6. Subsequently, the results of section A-A' in pit geometry design were applied for slope geometry modeling using the Slide software.

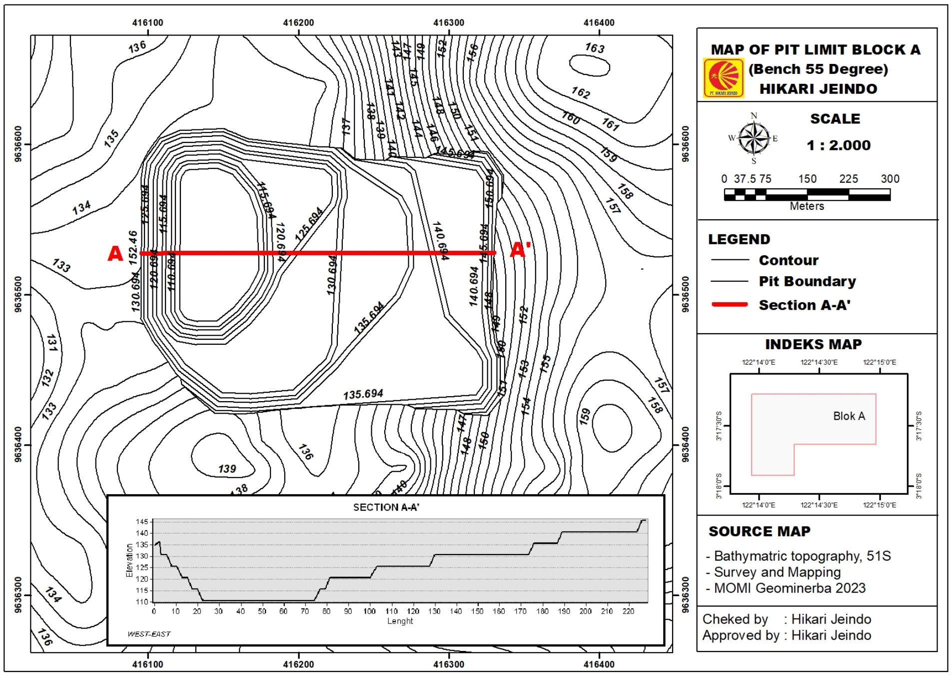


Figure 4. Section A-A' for angle of slope bench 55°.

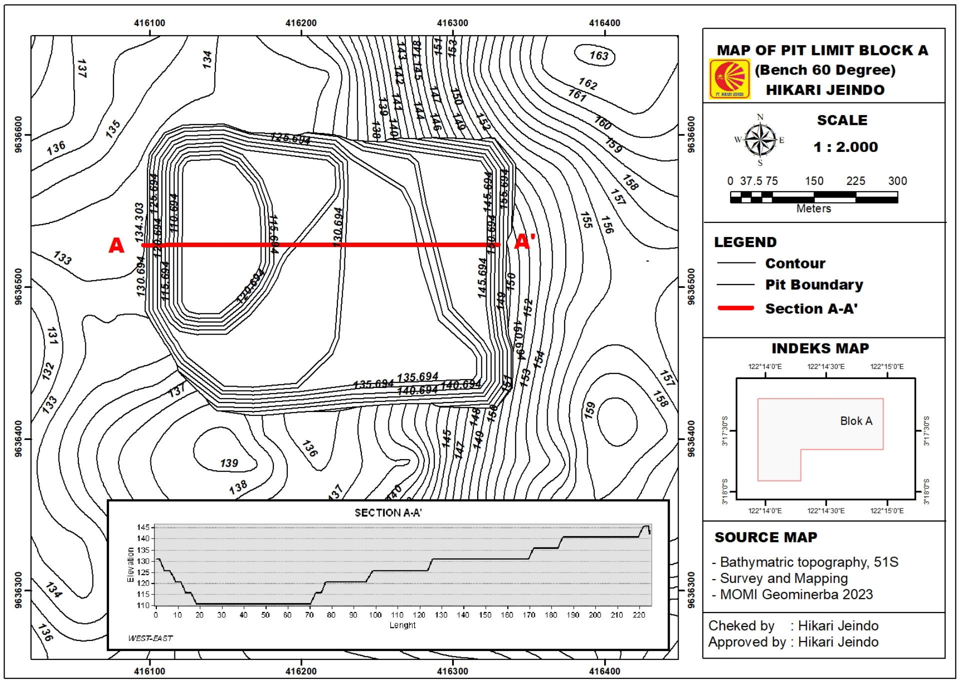


Figure 5. Section A-A' for angle of slope bench 60°.

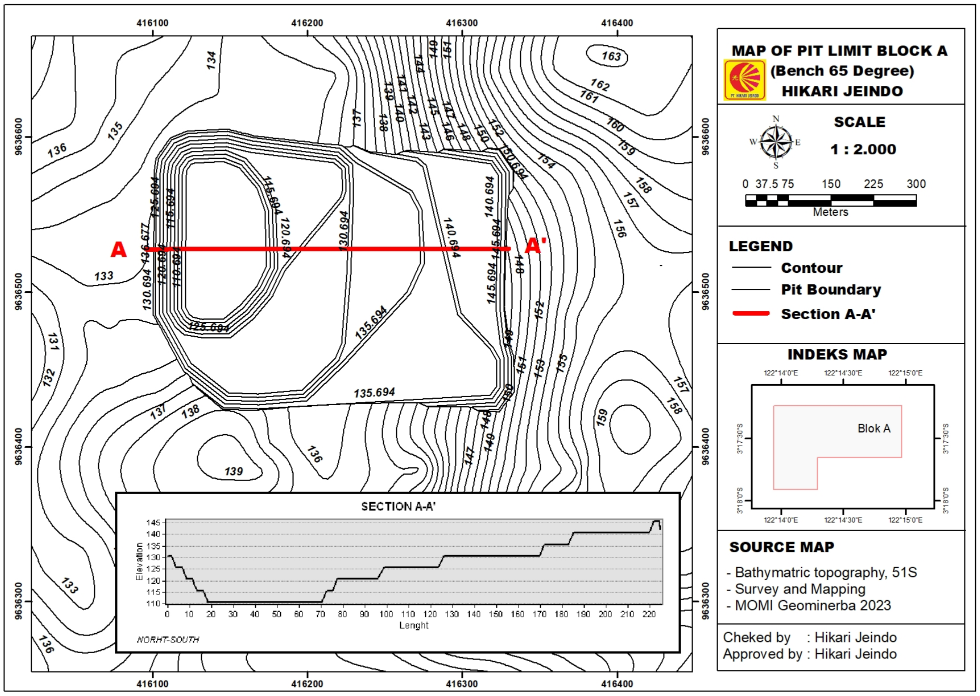


Figure 6. Section A-A' for angle of slope bench 65°.

3.7.1. Geometry of slope design in pit 1 with slope angle of 55° for each bench.

Based on section AA's results, slope geometry design was created with an angle of 55° for each bench. The results of this slope angle design included the overall slope angle, overburden stripping ratio, and ultimate pit limit. Based on slope geometry design, slope stability analysis was conducted using slide software 2D. Slope geometry design 1 with slope angle of 55° is shown in Table 7 and Figure 7.

Table 6. Material properties data

Soil type	Depth (m)	Parameter			
		Unit weight		Cohesion (C)	Internal friction angle (φ)
		Dry (kN/m^3)	Wet (kN/m^3)		
Top soil	2	10,59	12,23	18,30	21,79
Limonite	5	11,26	13,45	23,65	25,12
Saprolite	6	14,28	16,04	18,52	34,54
Boulder	20	22,28	23,14	8,01	37,79

Table 7. Slope geometry design of pit 1

Bench	Length of bench (m)	Width bench (m)	The angle of slope (°)	Overall slope height (m)	Overall slope angle (°)
Bench 1	5,79	2,5	55°	17	41°
Bench 2	5	2,5	55°		
Bench 3	5	2,5	55°		
Bench 4	5	2,5	55°		

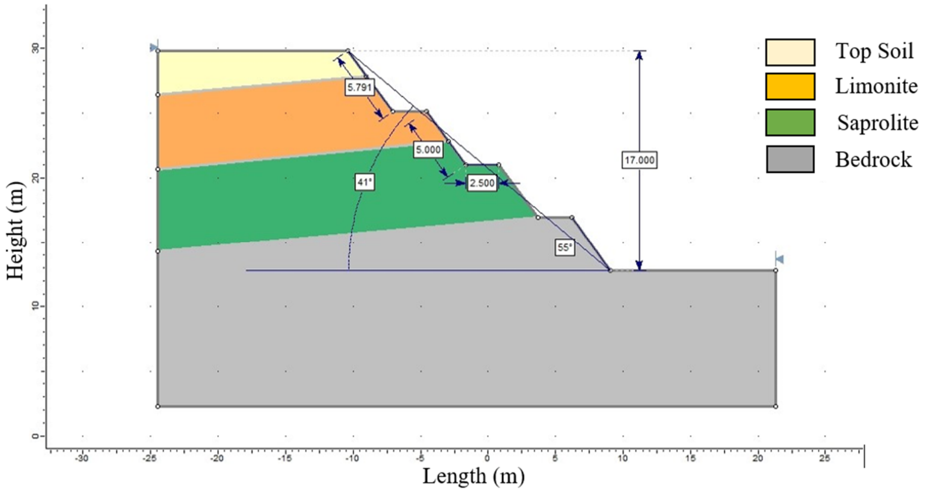


Figure 7. Slope geometry modeling pit 1 design.

3.7.2. Geometry of slope design of pit 2 with slope angle of 60° for each bench

Based on the previous method, slope geometry design two was created with slope angle of 60° for each bench. From section AA', the results of this slope angle design included a shallower overall slope angle, a smaller overburden stripping ratio as slope angle increases, and a different final ultimate pit limit. According to the slope geometry design obtained, slope stability analysis can be conducted using the Slide software. Slope geometry design 2 with slope angle of 60° is shown in Table 8 and Figure 8.

3.7.3. Geometry of slope design of pit 1 with slope angle of 65° for each bench

Slope geometry design 3 was created with slope angle of 65° for each bench, following the same method. Similarly, from section AA', the results of this slope angle design included a shallower overall slope angle, a lower overburden stripping ratio as slope angle increases, and a different final ultimate pit limit. Based on slope geometry design obtained, slope stability analysis was conducted using the Slide software. Slope geometry design 3 with an angle of 65 can be seen in Table 9 and Figure 9.

4. Discussion

4.1. Analysis of stability of the mine slope

Slope stability analysis was conducted to understand the impact of slope geometry changes resulting from open-pit mining expansion. The alterations in slope geometry of mining pit focused on modifying the single slope angle at each bench, leading to variations in the stripping ratio values and the final ultimate pit limit. The input material data used in slope stability analysis included the physical and mechanical properties of slope components. From the three designs of mining slope geometry with different angle variations at each bench, slope safety factor values were obtained through slope stability analysis using the Slide 2D modeling software. Simultaneously, slope geometry design with the smallest stripping ratio value was determined. Figures 10, 11, and 12 show the result of slope stability analysis modeling.

4.2. Slope stability analysis of pit 1

Slope stability analysis of pit geometry design 1 with overall angle of 41° showed safety factor value of 1.79 with a probability of failure at 0%. This value showed that both the individual and overall slope were in a safe condition, according to the regulations of the Ministry of Energy and Mineral Coal Resources and Bowles' criteria. From this slope geometry design, the tonnage of overburden and ore materials to be excavated was determined. The results showed 253,275 MT of overburden, 358,500 tons for an average Ni content of 1.30%, and 105,225 tons for an average Ni content of 1.85%. Based on the threshold of the maximum stripping ratio value set by Pt. Hikari Jeindo at 3, the obtained stripping ratio value from geometry design was 2.4, which showed economically feasible for excavation. The results of the analysis are presented in Table 10 and Figure 10.

Table 8. Slope geometry design of pit 2

Bench	Length of bench (m)	Width bench (m)	Angle of slope	Overall slope height (m)	Overall slope angle
Bench 1	4,63	2,5	60°	17	44°
Bench 2	5	2,5	60°		
Bench 3	5	2,5	60°		
Bench 4	5	2,5	60°		

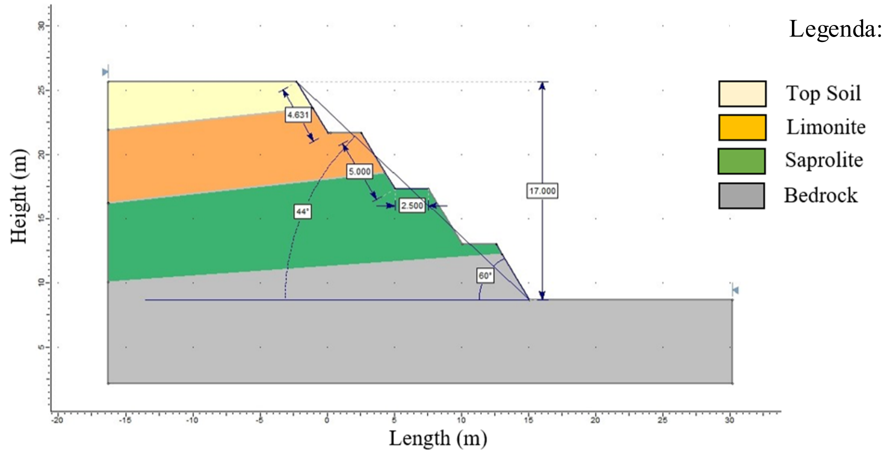


Figure 8. Slope geometry modeling pit 2 design

Table 9. Slope geometry design of pit 3

Bench	Length of bench (m)	Width bench (m)	Angle of slope	Overall slope height (m)	Overall slope angle
Bench 1	3,83	2,5	65°	17	48°
Bench 2	5	2,5	65°		
Bench 3	5	2,5	65°		
Bench 4	5	2,5	65°		

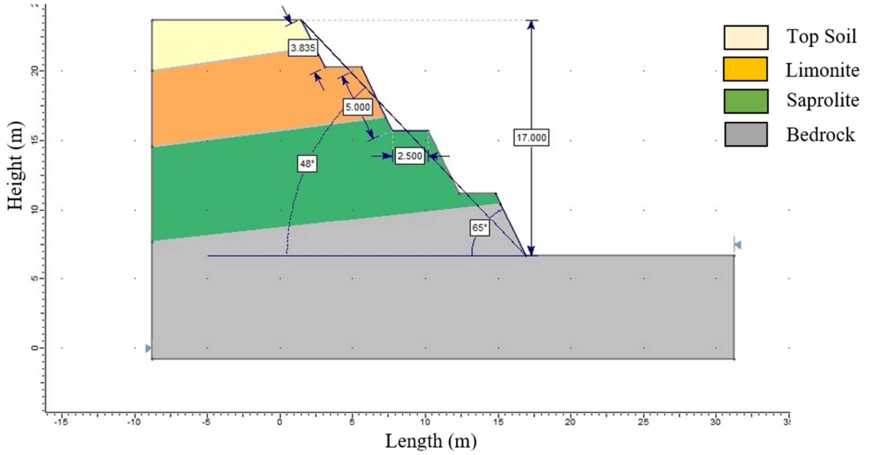
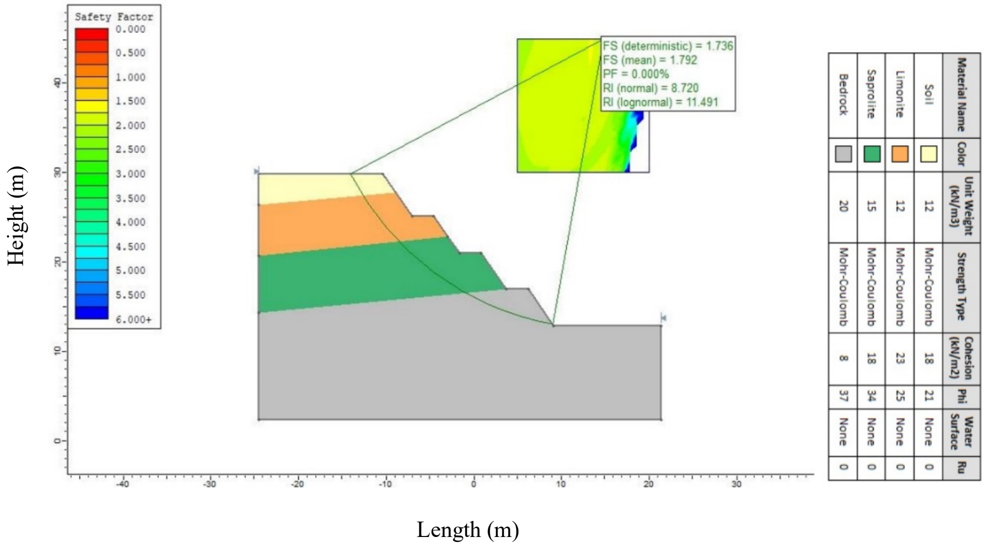


Figure 9. Slope geometry modeling pit 3 design.

Table 10. Analysis of slope stability in Pit 1 design.

Bench	FoS	Probability of failure (%)	Description
Bench 1	3,15	0,000	Stable
Bench 2	4,12	0,000	Stable
Bench 3	2,9	0,000	Stable
Bench 4	1,87	0,000	Stable
Overall	1,79	0,000	Stable



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kN/m2)	Phi	Water Surface	Ru
Soil	☐	12	Mohr-Coulomb	18	21	None	0
Limonite	■	12	Mohr-Coulomb	23	25	None	0
Saprolite	■	15	Mohr-Coulomb	18	34	None	0
Bedrock	■	20	Mohr-Coulomb	8	37	None	0

Figure 10. Pit 1 analysis of slope stability.

4.3. Slope stability analysis of pit 2

Slope stability analysis of pit geometry 2, with overall slope angle of 44°, showed a safety factor of 1.66 and a low probability of failure at 0%. This showed that slope conditions for both individual and overall slope remained stable, following the regulations of the Ministry of Energy and Mineral Coal Resources and Bowles' criteria. Based on slope geometry design, it was discovered that the tonnage of overburden and ore materials to be excavated slightly decreases, amounting to 240,025 tons of overburden, 345,250 tons for an average Ni content of 1.30%, and 105,225 tons for an average Ni content of 1.85, with a resulting stripping ratio value of 2.28. The steeper slope angle influenced the decrease in the stripping ratio value, reducing the limit of overburden stripping in the upper layer and low-grade ore material in the middle layer. In contrast, the quantity of high-grade ore material obtained in the lower layer remains the same. Therefore, based on the obtained stripping ratio value from geometry design, it remained economically feasible for excavation. The analysis results are presented in Table 11.

Table 11. Analysis of slope stability in pit 2 design.

Bench	FoS	Probability of failure (%)	Description
Bench 1	3,26	0,000	Stable
Bench 2	3,44	0,000	Stable
Bench 3	2,87	0,000	Stable
Bench 4	1,84	0,000	Stable
Overall	1,66	0,000	Stable

4.4. Slope stability analysis of pit 3

Slope stability analysis of pit geometry 3, with an overall slope inclination angle of 48°, yielded a safety factor of 1.55 and a collapse probability of 0%. This showed that slope conditions for both individual and overall slope remained stable, following the Ministry of Energy and Mineral Resources regulations for coal and Bowles' criteria. Based on this slope geometry design, the tonnage of overburden and ore materials to be excavated slightly decreased, amounting to 231,150 tons of overburden, 345,250 tons for an average Ni content of 1.30 %, and 105,225 tons for an average Ni content of 1.85, with a resulting stripping ratio value of 2.19. The decrease in the stripping ratio value was significantly influenced by the steeper slope angle, reducing the limit of overburden stripping in the upper layer. In contrast, the quantity of low-grade ore material in the middle layer and high-grade ore material in the lower layer remained unchanged. Therefore, the design could be considered the most economically feasible condition for excavation compared to the first and second geometry designs. The analysis results are shown in Table 12.

4.5. Sensitivity analysis of material

Sensitivity analysis is carried out to assess the degree of sensitivity of characteristic parameter changes to safety factor variations within a modeling framework. This analysis is conducted based on a uniform percentage change of 100% using the Slide, V. 6.0 software. The results of the sensitivity analysis of rock characteristic parameters are as follows:

4.5.1. Unit weight (c)

Based on the sensitivity analysis results using the Slide software the weight of the material is shown in the graph in Figures 13, 14, and 15, indicating the unit weight stability diagrams using the Bishop method. These diagrams showed that limonite and saprolite layers have high sensitivity based on total slope measurements. However, there was an inverse relationship between the sensitivity of fragmented materials and safety factor (FoS) values, showing that as the unit weight of the material increased, FoS values decreased. Based on the graphs, it was discovered that the unit weight served as a driving force, triggering soil instability on slope. An increase in unit weight was inversely proportional to safety factor. This showed that higher unit weight values corresponded to lower safety factor values on slope.

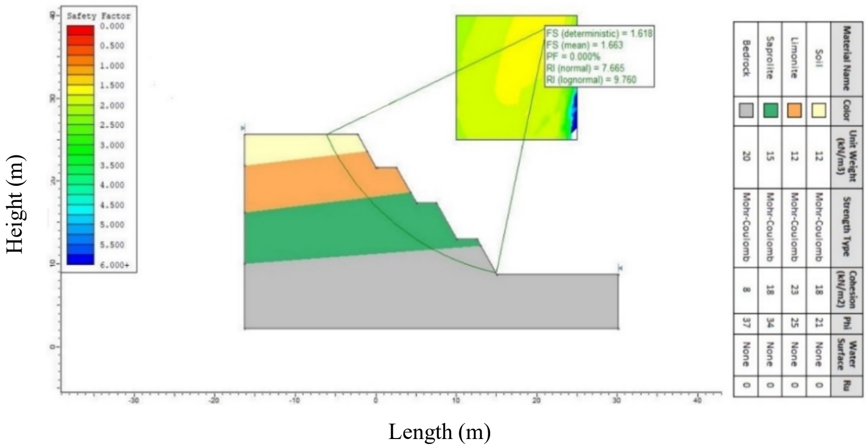


Figure 11. Pit 2 analysis of slope stability.

Table 12. Analysis of slope stability in pit 3 design.

Bench	FoS	Probability of failure (%)	Description
Bench 1	4,01	0,000	Stable
Bench 2	3,45	0,000	Stable
Bench 3	2,59	0,000	Stable
Bench 4	1,83	0,000	Stable
Overall	1,55	0,000	Stable

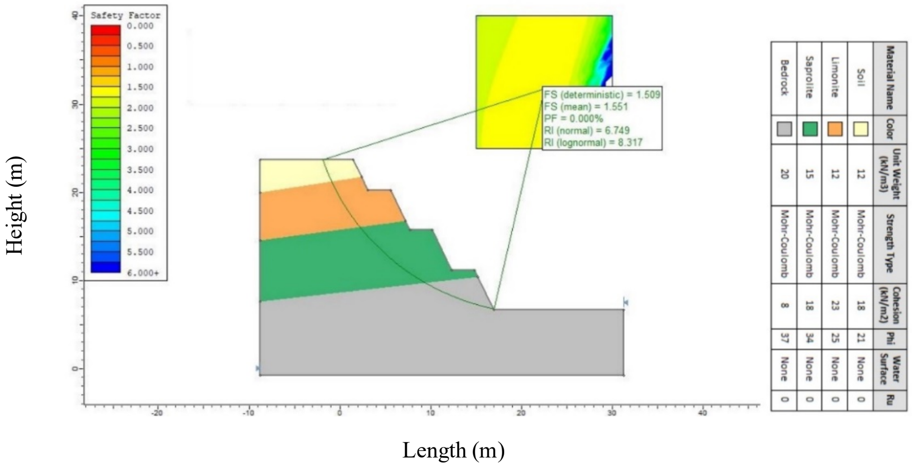


Figure 12. Pit 3 analysis of slope stability

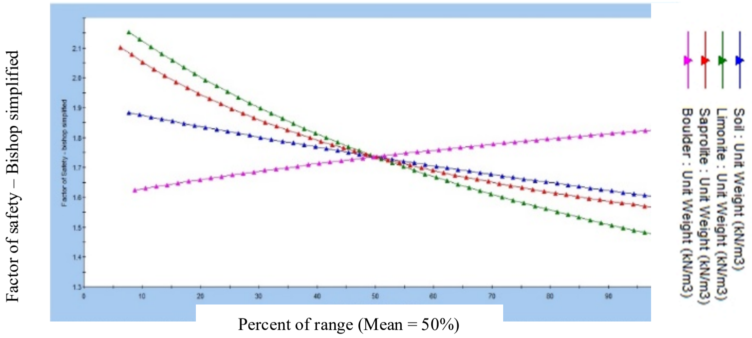


Figure 13. Diagram of sensitivity analysis unit weight in pit 1.

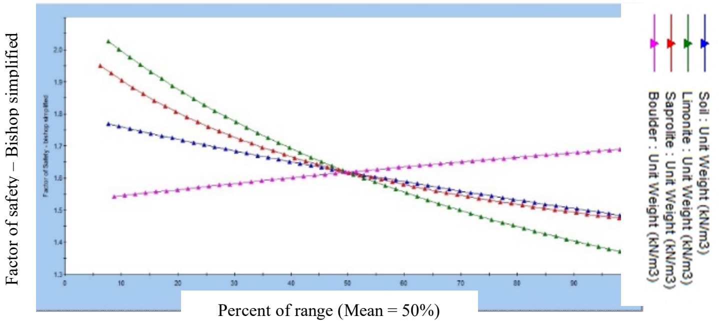


Figure 14. Diagram of sensitivity analysis unit weight in pit 2.

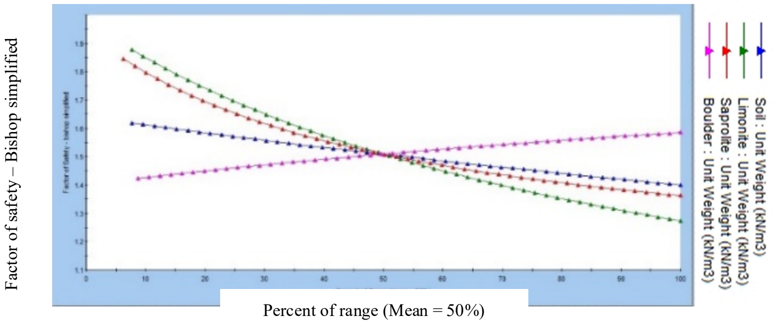


Figure 15. Diagram of sensitivity analysis unit weight in pit 3.

4.5.2. Cohesion (C)

Cohesion represents the attractive forces between particles within the soil, which is expressed in weight/unit area. Generally, the cohesion of rock increases as the shear strength increases. This relationship is presented in Figures 16, 17, and 18, showing the material sensitivity in each pit design. These graphs show that cohesion values play a significant role in calculating the factor of safety using the Runner method, indicating the direct proportionality of cohesion values to FoS values. Consequently, as the percentage of cohesion values increases, the FoS values on slope also increase, showing higher stability and a safer condition.

4.5.3. Internal friction angle (φ)

The ratio of normal stress to shear stress in soil material forms the internal friction angle. To assess the level of sensitivity of the internal friction angle, the values presented in Figures 19, 20, and 21, are used. The graphs show that the mechanical property of the internal friction angle (φ) significantly influences the variation in the safety factor values. The internal friction angle also possesses restraining characteristics that stabilize slope against driving forces. These graphs showed that the internal friction angle is directly proportional to safety factor values. Specifically, as the percentage of the internal friction angle increases, the safety factor values on slope rise, signifying more excellent stability.

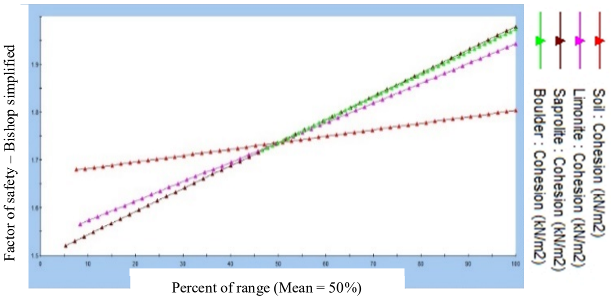


Figure 16 Diagram of sensitivity analysis for cohesion pit 1.

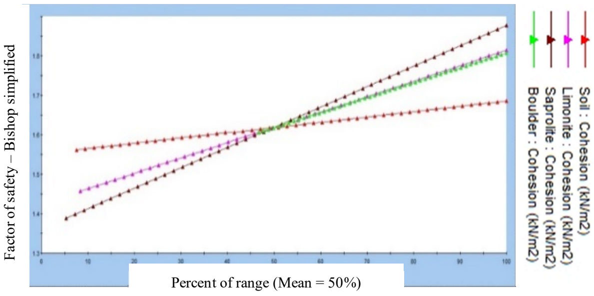


Figure 17 Diagram of sensitivity analysis for cohesion pit 2.

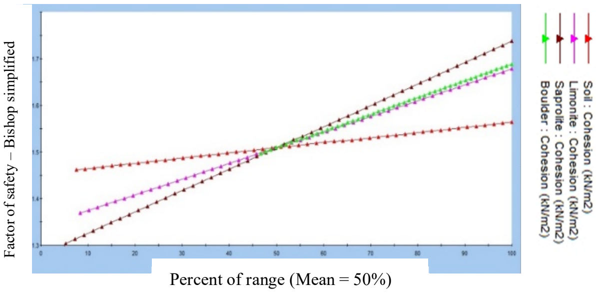


Figure 18. Diagram sensitivity analysis of cohesion pit 3

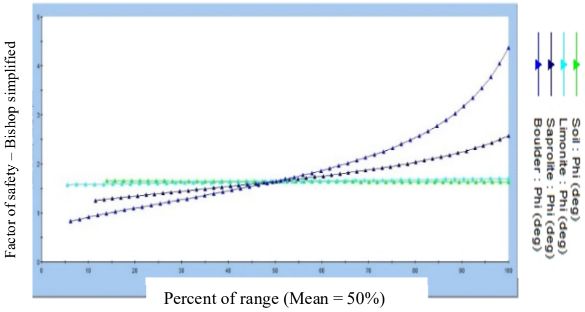


Figure 19. Diagram of sensitivity analysis for internal friction angle pit 1.

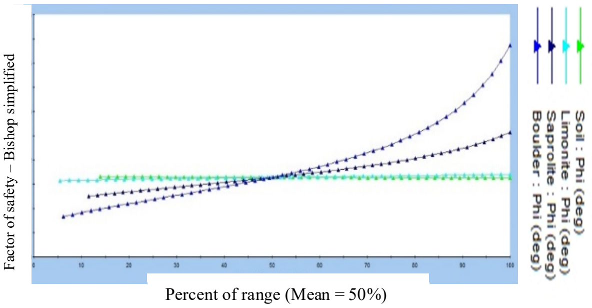


Figure 20. Diagram of sensitivity analysis for internal friction angle pit 2.

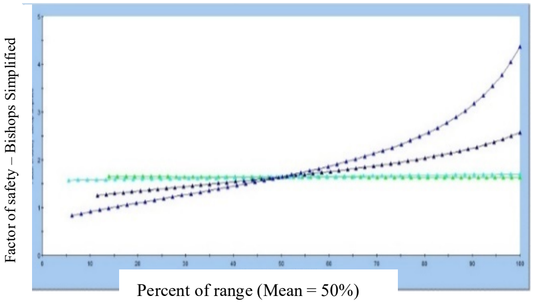


Figure 21. Diagram of sensitivity analysis for internal friction angle pit 3.

4.6. Influence of pit opening geometry on slope stability

The analysis results showed that geometry of pit opening had a significant impact on slope stability. Safety factor values of this research block showed that pit design geometry played an essential role in determining slope stability. In the diagram illustrating the influence of geometry on slope stability, it was observed that as slope angle increased in both height and magnitude, safety factor values decreased. The decrease was observed occurred due to an increase in slope height, for slope with a constant slope angle. Consequently, the soil shear strength becomes higher, resulting in the requirement of a greater resisting force.

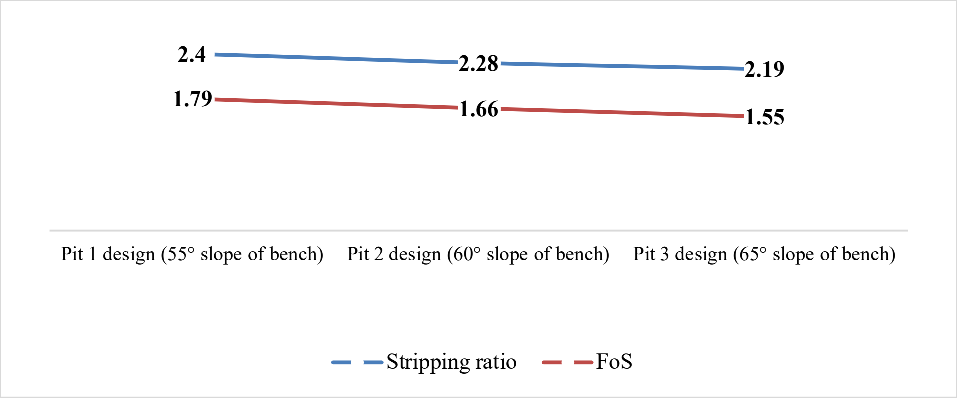


Figure 22. Relation between slope geometry with FoS, SR.

4. Discussion

The simplified 2D Slide Bishop modeling analysis provided a clear understanding of the impact of changes in pit geometry. This included single and overall slope angles, with final mining limits, and stripping ratios, on slope safety factor [3, 13, 16, 20, 22]. In this research work, the impact of mining pit expansion on slope stability was effectively shown through numerical modeling. The data indicated by technical and economic variables such as stripping ratio, cutoff grade, block economic value, and open-pit slope were considered essential parameters in the design and production planning process [3], providing valuable insights for decision-making.

The three optimal slope angle values obtained from the simulations showed that angles ensuring slope safety also had minimal stripping ratios. The changes in pit expansion geometry guaranteed slope stability, while offering economic benefits in terms of minimal stripping ratios. The additional benefits of numerical modeling in Slide 2D included obtaining the probability of failure values and sensitivity analysis of input properties. Furthermore, the probability of failure analysis was used to validate slope safety factor values. In contrast, sensitivity analysis of material properties successfully identified potential changes in the dominant factors affecting safety due to variations in material properties.

The use of 2D Slide limit equilibrium numerical modeling method in this research offered the benefits of relatively short analysis time and cost-effectiveness compared to other methods, such as radar slope stability analysis (SSR) [21]. Although this research work showed that using the 2D limit equilibrium numerical modeling method provided significant results, some limitations were observed in comprehensively interpreting the existing slope conditions. Consequently, further research should consider using 3D numerical modeling to compare and validate stability conditions of the entire mining slope area, specifically concerning the potential for instability in expansion mining pit.

5. Conclusions

Based on the results obtained, the following conclusions were obtained:

1. The optimal and economically viable slope geometry for pit Block A of PT Hikari Jeindo had a base length of 5 meters, a minimum base width of 2.5 meters, and a base slope angle of 65°.
2. The value of the stripping ratio was 2.19, while several safety factor values were obtained for the ultimate pit limit design. These included 1.79, 1.66, and 1.55 for pit designs 1, 2, and 3 across all benches with a probability of failure of 0%. Furthermore, it was observed that as slope angle increased, the stripping ratio decreases.

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تأثیر گسترش معدن روباز بر پایداری شیب در هیکاری جی‌ندو، لانگیکیما، کوناوه شمالی، اندونزی

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چکیده:

گسترش پیت معدنی با افزایش خطر ناپایداری شیب و هزینه های بالا همراه است. این به این دلیل است که تغییرات در هندسه شیب معدن به طور قابل توجهی بر پایداری شیب تأثیر می گذارد، نسبت سلب را تغییر می دهد و به طور بالقوه تداوم عملیات معدن را تهدید می کند. بنابراین، این کار تحقیقاتی با هدف بررسی تأثیر تغییرات هندسه پیت معدنی بر پایداری شیب برای ارائه بینشی به ایمنی، تضمین‌های اقتصادی و اطمینان از پایداری عملیات معدنی انجام شد. این کار تحقیقاتی با روش مدل‌سازی عددی دوبعدی با استفاده از نرم‌افزار Slide V. 6.0 Rocscience برای تحلیل هندسه پیت معدن و تأثیر آن بر عوامل ایمنی شیب استفاده شد. این تحقیق در Pit Block A از Pt انجام شد. Hikari Jeindo، مدیریت فعالیت‌های استخراج نیکل در منطقه Langgikima، شمالی Konawe، Regency، استان سولاوسی جنوب شرقی، اندونزی. نتایج نشان داد که روش مدل‌سازی با موفقیت تغییراتی را در هندسه شیب نشان می‌دهد و از عوامل ایمنی شیب مطمئن و مقرون به صرفه است. با این حال، برای به دست آوردن درک جامع‌تری از شرایط پایداری شیب، یک روش مدل‌سازی عددی سه‌بعدی برای گرفتن منطقه تحت‌تاثیر گسترش پیت معدن مورد نیاز است.

کلمات کلیدی: هندسه پیت، پایداری شیب، نسبت سلب، مدل‌سازی عددی.